Atmospheric Compensation for Uplink Arrays via Radiometry

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Introduction

Uplink arrays for communications applications are gaining increased visibility within the NASA and military community due to the enhanced flexibility and reliability they provide. When compared with the conventional large, single aperture antennas currently comprising the Deep Space Network (DSN), for example, smaller aperture antenna arrays have the benefits of providing fault tolerance (reduced single-point failure), reduced maintenance cost, and enhanced capabilities such as electronic beam-steering and multi-beam operation. However, signal combining of antenna array elements spaced many wavelengths apart becomes problematic due to the inherent instability of earth's turbulent atmosphere, particularly at the frequencies of interest to the DSN (i.e., Ka-band). Degradation in the power combining of the individual elements comprising the array arises due to uncorrelated phase errors introduced as the signals propagate through the troposphere. It is well known that the fundamental source of this error is due to the inhomogeneous distribution of water vapor in the atmosphere [1]. Several techniques have been proposed to circumvent this issue, including the use of phase calibration towers and a ‘moon bounce’ to generate a feedback loop which would provide a means of intermittent calibration of the system phase errors (thermal drifts, atmosphere) [2,3]. However, these techniques require re-positioning of the antenna elements to perform this operation which ultimately results in reduced system availability. And, though they are sufficient for compensating for slow varying phase drifts, they are insufficient to compensate for faster varying phase errors, such as those introduced by the atmosphere. In this paper, preliminary radiometry and interferometry measurements collected by the NASA Glenn Research Center are analyzed and indicate that the use of *optimized* water vapor radiometers as a feedback system in a communications platform could provide the necessary atmospheric compensation technique to enhance the beamforming of uplink arrays.

Interferometer/Radiometer System

A well-tested means of characterizing the tropospheric phase stability above a radio observatory are two-element interferometers observing unmodulated beacons of geostationary satellites [1]. The GRC site test interferometer is configured at Goldstone, CA, on a 256 m east-west baseline and tracks a 20.199 GHz beacon on the geostationary communication satellite, Anik-F2, at an elevation angle of 48.5 degrees. A full description of the interferometer hardware is provided in [4] and depicted below in Figure 1.

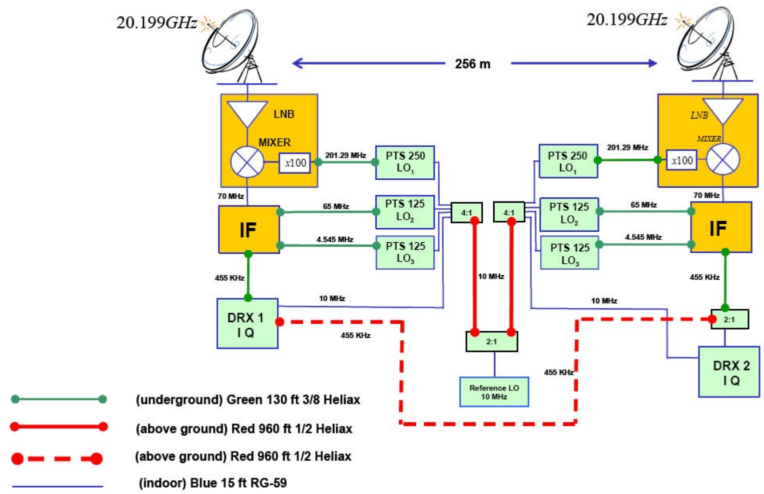

Figure 1 – Block diagram of Goldstone site test interferometer.

Each element of the interferometer consists of a 1.2 m offset-fed parabolic reflector with antenna half-power beamwidth of 0.7 degrees. A 10 MHz GPS-disciplined Rubidium oscillator provides the reference timing for all system operations and measurement are recorded at a rate of 1 Hz. In addition to the phase measurements provided by the interferometer, the same two antennas are equipped with 27.5 GHz total power radiometers (TPR) utilizing a 50 MHz bandwidth. These radiometers are derived from the Advanced Communications Technology Satellite (ACTS) terminals and provide concomitant radiometer measurements with the phase measurements [5]. It should be noted that the radiometer design presently deployed represents a sub-optimal design for accurately detecting water vapor, but it is suitable to provide a proof-of-concept.

Interferometer/Radiometer Data Correlations

The phase data recorded by the interferometer is calibrated via a second-order polynomial fit over 10-minute blocks to remove the effects of satellite motion and slow-varying system-induced phase drifts (i.e., system thermal gradients throughout the day) [6]. The remaining phase fluctuations are those due solely to the atmosphere. Radiometer data calibration involves removal of mean voltage differences over the same 10-minute block period. This is sufficient for the purposes of this analysis as the differential phase is a relative measurement and we are only interested in fast-varying phase fluctuations.

Figure 2 shows a time series comparison of the raw radiometer output voltage and the calibrated phase time series. From the plot, it is readily observed that during periods of high phase fluctuations (high turbulence, high water vapor content), the 27.5 GHz TPR's are capable of resolving these fluctuations. A quantitative inspection of the correlation coefficient between differential phase and radiometer voltage is provided in Figure 3 and indicates that during the hours of 12:00 - 16:00 GMT, phase fluctuations are minimal and the correlation coefficient between radiometer and phase delay is ~0.2. However, during the last four hours of the day (20:00 - 24:00 GMT), the correlation coefficient improves to ~0.7. The poorer correlations during quieter times of the day are attributable to the fact that 27.5 GHz is not the optimal viewing frequency for water vapor.

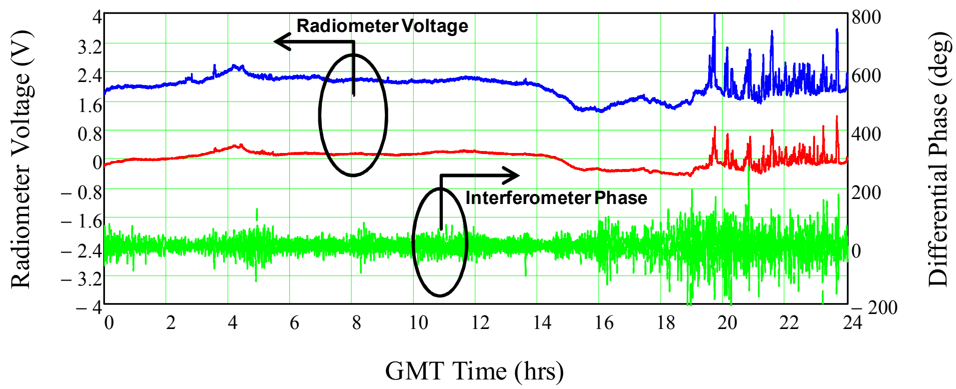

Figure 2 – Plot of radiometer voltages and interferometric phase for 9/18/2008.

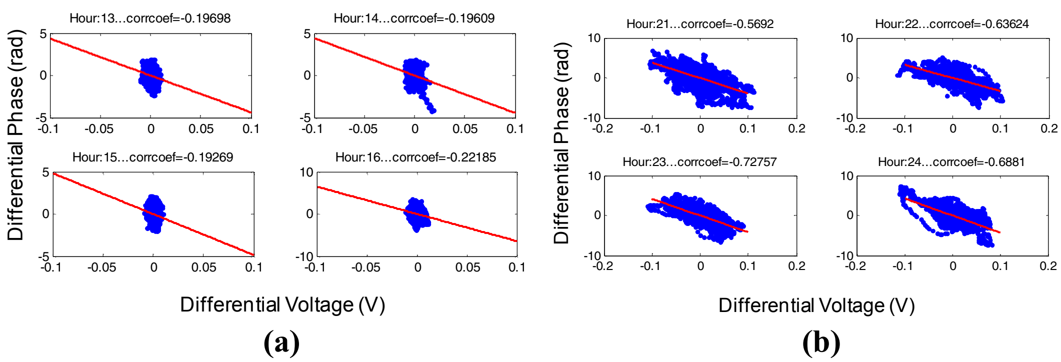

Figure 3 - Plot of correlation between differential phase (interferometer) and differential voltage (radiometer) for (a) hours 13-16 GMT and (b) hours 21-24 GMT on 9/18/2008.

Theoretical Performance of Radiometer-Enhanced Array

The data from the radiometer and interferometer are now utilized to determine the theoretical improvement factor of a two-element array using radiometry-based compensation. For the simulation, a two element array identical to the interferometer setup is modeled (i.e., 256-m baseline, 48.5° elevation angle, 20.199 GHz). Radiometer data are scaled via the correlation factor between radiometer voltage and phase over a 1-hour 'moving block'. Phase errors are removed from the uncompensated phase data by removing the scaled radiometer measurement on a point-by-point basis. The resulting improvement in phase rms is shown in Figure 4. Though most of the day indicates little/no improvement, the latter portion of the day, where turbulence is high and radiometer-interferometer correlation is strongest, a ~30% reduction in root-mean-square (rms) phase is realized. From the measured data, this corresponds to an improvement of ~0.8 dB in beamforming efficiency over this time interval.

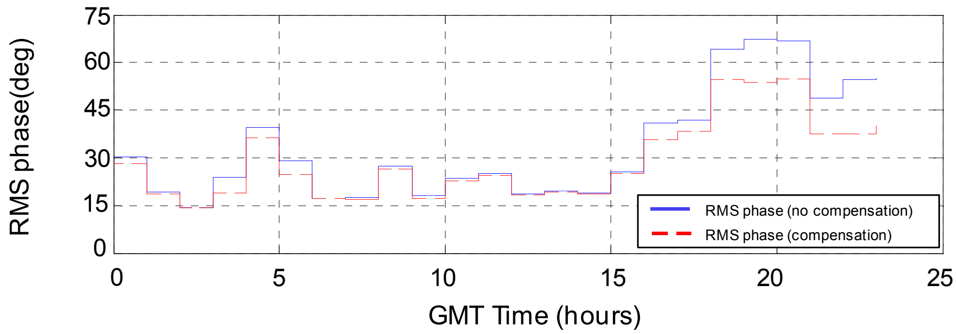

Figure 4 – Plot of rms phase time series with no phase compensation (solid) and with phase compensation (dashed).

Conclusions

A proof-of-concept power combining enhancement scheme is proposed for an uplink array of widely spaced antenna elements through the utilization of a radiometer feedback system. The radiometer system provides near real-time compensation for improving the effective isotropic radiated power (EIRP) of an array, which could provide the optimal solution to array beamforming at Ka-band frequencies via atmospheric compensation. This technique is demonstrated with a sub-optimal 27.5 GHz radiometer and could further be improved with the use of a more sensitive water vapor radiometer.

References

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